24P

NASA TECHNICAL TRANSLATION NASA TT F 15,617

FLIGHT CONTROL PROBLEMS FOR STEEP APPROACHES

R. Brockhaus

Translation of: "Flugfuehrungsprobleme des Steilanfluges," Technische Universitaet Braunschweig, Zentralstelle der Luftfahrtdokumentation, DGLR Paper 73-027, presented at the Symposium on New Approach and Landing Techniques, May 2-4, 1973, 34 pp.

N74-27493

(NASA-TT-F-15617) FLIGHT CONTROL PROBLEMS FOR STEEP APPROACHES (Scientific Translation Service) 34 p HC $4.75 CSCL 01C Unclas G3/02 41624

RECEIVED NASA STI FACILITY INPUT BRANCH JUL 1974

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. JUNE 1974

STANDARD TITLE PAGE

1. Report No. NASA TT F 15,617	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle FLIGHT CONTROL PROBLEMS FOR STEEP APPROACHES		5. Report Date JUNE 17, 1974 6. Performing Organization Code
7. Author(s) R. BROCKHAUS		8. Performing Organization Report No. 10. Work Unit No.
9. Performing Organization Name and Address SCITRAN Box 5456 Santa Barbara, CA 93108		11. Contract or Grant No. NASw-2483 13. Type of Report and Period Covered Translation
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

Translation of: "Flugfuehrungsprobleme des Steilanfluges," Technische Universitaet Braunschweig, Zentralstelle der Luftfahrtdokumentation, DGLR Paper 73-027, presented at the Symposium on New Approach and Landing Techniques, May 2-4, 1973, 34 pp.

16. Abstract

STOL approach methods are discussed, including trajectory angles of 6° and 12°. Past STOL American projects are reviewed. It is found that STOL steep approaches involve the following: design of flight control system, area navigation system, thrust control system, development of microwave guide beam systems, retraining of pilots, greatly increased reliability requirements on all systems. The information requirements for these approaches are compared with the information required for conventional ILS landings. Traffic control problems and traffic integration problems with conventional traffic are discussed.

17. Key Words (Selected by Author(s))	18. Distribution Statement
	Unclassified - Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	30	

SUMMARY

Aircraft with steep landing characteristics will contribute /1* to the solution of environmental problems associated with air travel, such as noise generation and space requirements for long landing runways. Also, STOL traffic will make use of airports and aircraft in a more optimum way which will increase the efficiency of air travel.

The introduction of steep landings in general aviation depends greatly on the developments in the area of flight control. It depends on the availability and costs associated with the ground based and onboard instruments which are required for aircraft carrying out steep landings in addition to the equipment already installed. The expenditure required to expand and improve the control, display, and navigation systems limits the performance variables, such as the steepness of the approach or the density of subsequent landings in time. Also, these factors will decide whether economical STOL operation is at all possible.

The flight control problems associated with vertical landings have been the reason why this type of landing has been partially rejected. Therefore, today, steep landings are being considered which combine the use of the aircraft and the landing techniques in a way quite similar to the classical jet traffic. The equipment necessary for flight control during steep landings is already available. Because of economy, STOL traffic will be restricted to approach angles of around 6°.

*Numbers in the margin indicate pagination of foreign text.

TABLE OF CONTENTS

I.	INTRODUCTION	1
2.	PREVIOUS STEEP APPROACH DEVELOPMENTS	2
3.	THE SITUATION OF THE PILOT DURING STEEP APPROACHES	7
4.	NECESSARY DISPLAYS AND CONTROLLER AIDS	13
5.	TASK DIVISION BETWEEN THE PILOT AND THE FLIGHT CONTROL SYSTEM	21
6.	NAVIGATION AND TRAFFIC CONTROL PROBLEMS	22
7.	FUTURE DEVELOPMENT	26
8.	FINAL REMARKS	28
REFERENCES		28

FLIGHT CONTROL PROBLEMS FOR STEEP APPROACHES

R. Brockhaus*

I. INTRODUCTION

STOL** traffic has been considered for many years as an extension of conventional civilian aviation. The introduction of steep approach trajectories is also being considered. The following results are desirable: /3

— noise reduction based on increased flight altitude in the vicinity of airports and because of the reduced engine thrust;

— increased touchdown accuracy, shorter landing runways, and therefore, reduced landing velocities;

— shorter overall times for short distance runs.

At the present time, this development is proceeding at full speed. This is being done by providing increased lift, improvement of the engines as well as development of new approach and navigation aids. This is why the suggestions for STOL traffic and the associated test projects are so numerous that today one cannot speak of a standard steep approach method. This means that the flight control problems for steep approach are very numerous and these can be completely different, depending on how one defines steep approach, what is to be achieved, and which aircraft configurations are used. In this paper we will only

*Technical University, Braunschweig.

**STOL = Short Take Off and Landing.

discuss the general problems and we will indicate how the flight control aids could be used to solve them. Therefore, we will restrict the numerous possibilities and will require maximum safety requirements, the best possible relief for the pilot, and high passenger comfort. These requirements are compared with minimal requirements, such as strict economy considerations, which provide no comfort at all and which have been investigated in a few test programs by American airlines and NASA.

2. PREVIOUS STEEP APPROACH DEVELOPMENTS /4

The development of steep approach is characterized as a path which leads from the ideal model of vertical landings to minimal solutions, which can be carried out without a great deal of effort using conventional aircraft. We can distinguish three directions of development:

a) "Moderate" VTOL aircraft, i.e., projects derived from vertical takeoff aircraft with thrust augmentation during slow flight (thrust deflection, wing deflection, lifting engines, etc.) and with extremely short landing properties. As examples of this, we have the Bell X22, the Dornier Do 31, as well as the German V/STOL project definition of 1969. The extremely high approach angles which go up to 20° are characteristic for this, and the descent velocities are as high as 1600 ft/min (8 m/sec) [1].

b) True STOL aircraft. First of all, these are light aircraft with short landing properties, such as for example, the Dornier Do 28 Skyservant. Projects of the order of transport aircraft usually have aerodynamic or thrust-augmented high lift devices, such as externally blown flaps or augmentor wing. Examples of this are the Breguet 941 [2] and the specifications

for a "quiet experimental STOL" project [4]. Even though larger approach angles are possible, at the present time an angle of 7.5° is considered to be the upper limit. Angles of up to 20° are being investigated.

c) Use of conventional civilian aircraft with improved flight control aids, i.e., improvements in the approach and navigation system, in the displays, and in the control systems. As examples of this, we have the test programs of American airlines and NASA described below. They are characterized by broken approach profiles with a 6° inclination during the upper segment.

The concept of "fast VTOL aircraft" has been dropped because /5 of the great complexity and costs. True STOL developments will be part of the next aircraft generation, such as for example, the quiet STOL program of NASA. The first introduction of steep landings of the type of interest to airlines will be very close to present day aircraft, flying methods, and flight control systems. Several test programs have been carried out, especially in the United States, in order to determine the normal and extreme traffic conditions:

a) 1968 NASA/Boeing program using the Boeing 367-80 (707 prototype). There are straight and broken approach trajectories with trajectory angles up to 6°, delayed approaches, use of ILS and additional control aids (radar altitude and distance), use of integrated electronic displays using modified flight directors, additional measured variables, and television picture (see below) as well as extensive control aids such as forward thrust controller, automatic trim, lift control, and pitch rate command [5, 6]. This represents quite an investment in flight control aids.

b) 1968/69 test program of Eastern Airlines [2], [3] and later by American Airlines using a Breguet 941 A (McDonald Douglas 188) with the purpose of determining the flight operational requirements for STOL traffic. Area navigation with vertical control (Decca Omnitrac), radar altitude transponder, glide path flight indicator, and three-dimensional area navigation (Butler National Co. Vector Analog Computer), as well as inertial navigation and TALAR were used.

c) 1971 NASA/American Airlines. Two segment approaches (6°/2.5°) using the Boeing 720 B. Use of conventional ILS and /6
three-dimensional area navigation, the latter was also used for calculating the upper part of the glide path. Additional displays: adaptation of the flight director to the glide path break, four display lamps used as flight path indicators, as well as displays of the vector analog computer (reduced amount of equipment compared with b) [7].

d) 1971/72 American Airlines, computation and study on the use of propeller aircraft for STOL traffic [8, 9].

e) 1973 NASA/ United Airlines Program. Two-segment approaches (trajectory 4 — 7°) using Boeing 727-200 with special glide path computer and with the use of barometric altitude and DME, as well as McDonnel Douglas DC 3-61 with a three-dimensional navigation system. Modification of the flight director, especially for vertical trajectory control, as in program c), as well as modifications of the autopilot functions. It is desirable to have the steep approach be adapted as much as possible to conventional ILS approach, so that the additional equipment as well as the training effort for the pilot will be reduced to a minimum [10].

In Germany, since 1971, the Boderseewerk has carried out an STOL test program using the Dornier Do 28 Skyservant, in which a redundant flight control system is used and was developed for this purpose [11]. Recently, there have been developments in the area of display technology and approach aids. In addition to broken approach profiles they are also considering those which have a continuous curvature [12, 13].

This test program can be summarized as follows:

— the maintenance of a steeper approach trajectory as well as transitions between approach segments with different inclination angles means a situation exists which is different from the conventional approach. This requires increased performance by /7 the pilot.

— Steep approaches up to 7 ° trajectory angle can be flown without increased work load, if the corresponding improvements are made in the displays, flight control system and navigation aids (guide beam, etc.). This is true even for conventional jet aircraft with some restrictions.

— STOL aircraft are difficult to integrate in conventional air traffic. The advantages of STOL traffic can only be exploited by introducing new navigation aids (area navigation) and by improving the flight safety system.

— Airlines and pilots will only accept STOL operation if the procedures used are very close to conventional flight operations and if the amount of new equipment is low (in addition to economy).

— Passengers will only accept STOL traffic if the connections provided are more rapid and on time. Also, the same degree of comfort as in long distance jet travel will be required.

— One reasonable compromise between the amount of effort and the success (for example noise reduction) at the present time seems to be the use of a broken approach profile. The upper part has a 6° trajectory angle inclination and there is a transition to the usual ILS approach at an altitude of 400 feet.

— The lower part of the glide path can be specified by the ILS. The upper part can be calculated from other measurement data (precision navigation system, for example, inertial navigation or precise distance and altitude measurement), since no new guide beam system is available. Conventional ILS can be used for the lateral control.

— The additional information required by the pilots and which should appear in an integrated display is the following:

— altitude,
— distance from touchdown point,
— ground air speed,
— descent velocity, /8
— true and "potential" trajectory angle,
— ("Instantaneous flight path"),
— attitude and side slip angle,
— thrust level.

— New guidance displays are required, especially for vertical control and for introducing the transition into the various flight segments.

— Flight control systems available today are sufficient for moderate requirements. If the pilot load is not greater than for conventional approach, then it is necessary to have a completely integrated autopilot [10, 12]. In addition, it would

be advantageous to have a trajectory control according to the control wheel steering principle, such as in the Boeing 737 [6].

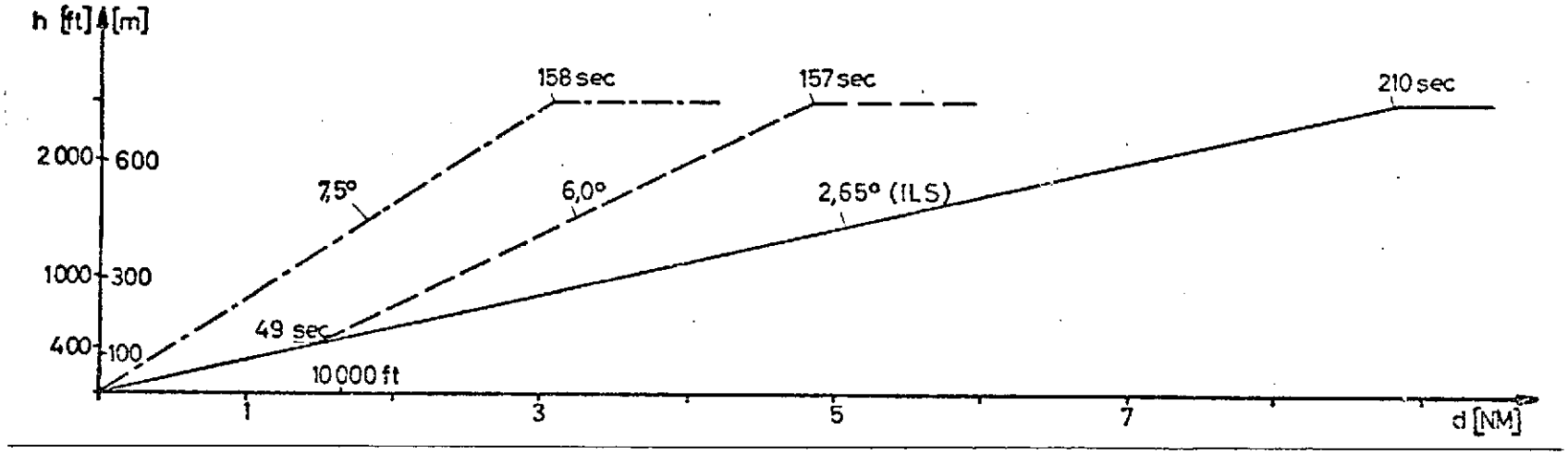
3. THE SITUATION OF THE PILOT DURING STEEP APPROACHES

In the case of conventional ILS approach, the pilot changes at a safe altitude of 2500 feet (760 m) from horizontal flight to a descending flight with a trajectory inclination of 2.65°, which at 155 kts (80 m/sec) approach velocity corresponds to a descent velocity of 730 ft/min (3.7 m/sec). He has enough time to stabilize the aircraft in this new stationary flight state. About 3-1/2 minutes later, he flies through the decision altitude of 100 feet (30 m) and he drops the descent velocity from 3.7 m/sec to about 0.6 m/sec (Figures 1 and 2).

In the case of steep descent on a straight guide beam of 7.5°, for example, the change of the flight state is considerably larger when the glide path is entered. If the descent velocity is not to exceed 1000 ft/min (5 m/sec),* then it is necessary to reduce ground speed to 77 kts (38 m/sec). This involves a large angle of attack change and the extension of flaps. Up to the /9 decision altitude of 100 feet, 2-1/2 minutes elapse. During this time the ground speed and descent velocity must be maintained very accurately. The high descent velocity must be reduced earlier than for ILS approach, i.e., the pullout arc already starts at an altitude of 100 feet, so that for constant ground speed and touchdown 100 feet behind the glide path transmitter, the time between the decision altitude and touchdown is 16 seconds, approximately.

---

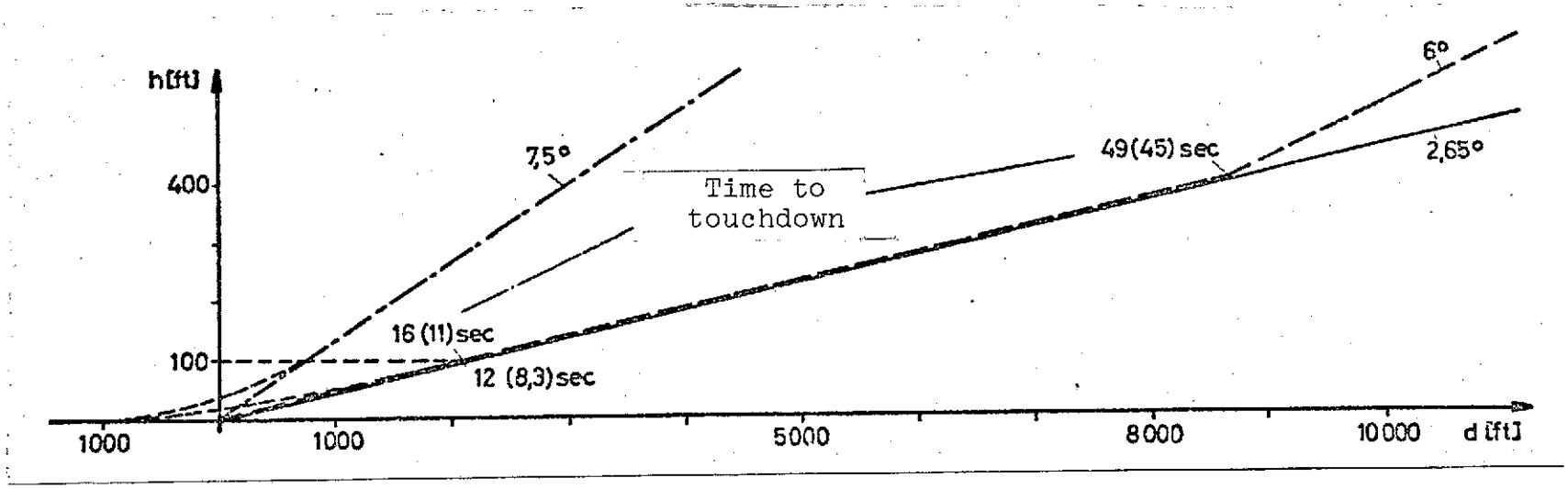
*In general, 1000 ft/min is considered to be the upper limit of permissible descent velocity in the vicinity of the ground [15].



——— Conventional ILS approach (Vo = 155 kts (80 m/sec)
—·—·— 7.5° Trajectory angle (Vo = 77 kts (38 m/sec)
----- Broken approach tracjectory (NASA tests)

$\dot{h}$ = 730 ft/min (3,7 m/sec)
$\dot{h}$ = 1000 ft/min (5 m/sec)
$\dot{h}$ = 1180 ft/min (6 m/sec)
and 530 ft/min (2,7 m/sec)
respectively

Figure 1. STOL approach profiles.



——— Conventional ILS approach (Vo = 155 kts (80 m/sec)
—·—·— 7.5° Trajectory angle (Vo = 77 kts *38 m/sec)
----- Broken approach trajectory (NASA tests)

$\dot{h}$ = 730 ft/min (3,7m/sec)
$\dot{h}$ = 1000 ft/min (5 m/sec)
$\dot{h}$ = 1180ft/min (6 m/sec)
and 530ft/min (2,7 m/sec)
respectively

Figure 2. STOL approach profiles.

In addition to the purely geometric considerations, we must consider the fact that the deviations from the normal flight path lead to an uncontrollable situation more rapidly and, therefore, less time is available in unpredictable situations for analyzing the situation and making the correct decisions. Therefore, deviations from the nominal trajectory must be detected earlier and must be corrected fast and effectively. This means that the pilot must have a better knowledge of the aircraft flight control system than for conventional approaches and he must have a better understanding of the measures to be taken under certain conditions.

Because of the increased work load on the pilot, often a two-segment approach has been suggested [5, 6, 7]. In the upper part, the trajectory angle is 6° and, at an altitude of 400 feet, it is transformed into a normal ILS approach (2.5° to 3°). This has the advantage that about 35 seconds before flying through the decision altitude, the descent velocity has already been reduced to more than one-half, and the final approach and pullout can be performed using ILS procedures. This advantage is offset by the additional difficulty of changing to another trajectory angle in the vicinity of the ground (400 feet), and only 35 seconds are available for stabilizing to these conditions.

In order to avoid such stepwise transitions, straight line /10
delayed approach trajectories have been suggested (with continuous drop in the ground speed [16]), as well as curved approach trajectories, in which for example the descent velocity must be maintained constant over a large part of the approach [12]. For this, a new approach aid must replace the ILS.

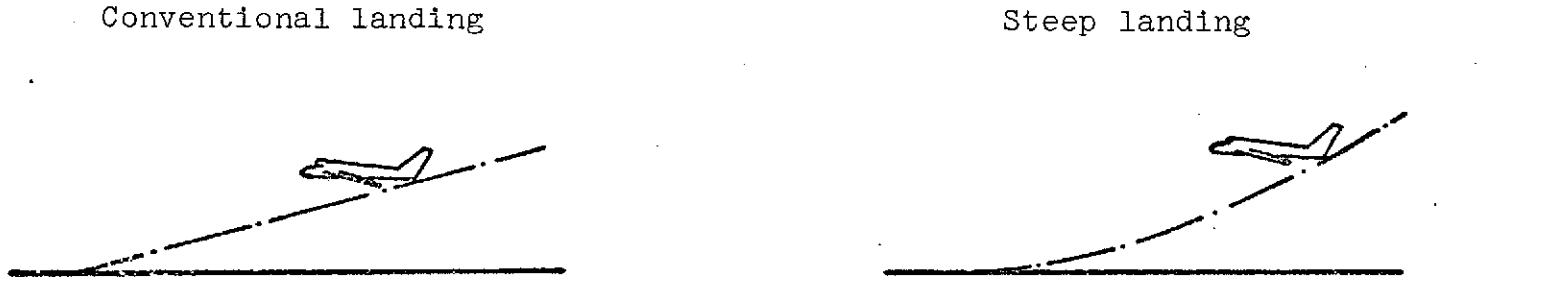
The special circumstances during steep approaches can be summarized as follows from the pilot's point of view:

— the trajectory parameters are not constant over longer time periods as in the case of ILS, but can change continuously;

— the pilot has less time to reflect (error analysis) in the case of unpredictable situations and for making decisions;

— since there is less time for stabilization of the individual flight segments, and because the deviations from the nominal trajectory are much more critical than for conventional approach, the accuracy requirements for maintaining the trajectory parameters are higher.

In addition to the required new flight trajectory reference for broken or curved approach trajectories, the pilot must have available more and better information on the flight situation, if his load is not to be higher than for conventional approaches. In addition, the flight control system should take over the job of stabilizing along the flight trajectory. This requirement is emphasized by the fact that for steep approaches, the flight properties are in general poorer than for conventional flight [12, 17]. In the case of low flight velocities in the vicinity of the minimum drag point, the phygoide and the tumbling oscillations are not damped as much and the influence of all-pass on the trajectory behavior (so-called ground speed instability) is annoying. In [17], it is shown that the influence of gusts is not necessarily higher than for conventional approach, but because of the small ground speed, the side wind influences and /11
shear wind influences are greater. In addition, the control effectiveness of the aerodynamic rudders is lower and the reaction time of the engines is about double [18] for greatly reduced thrust level, so that it becomes more difficult to maintain ground speed. These poorer flight properties must be



Almost constant { Velocities, Drift, Forward thrust } Variable

Therefore, additional requirements for steep landings:

1. Direct measurement of all state vairables
2. Measurements with reservations (partially differentiation)

Figure 3. Increased measurement requirements for steep approach.

compensated for by improved control units. This is especially true for instrument flight conditions.

Finally, whenever a trajectory change is carried out, the elevator, thrust, and trim actuators must be operated in a coordinated way, because their effects are coupled. In the case of unconventional aircraft configurations (controllable flaps/DLC, thrust deflection, wing deflection, etc.), there are additional parameters which must be set (flap angle, thrust vector angle, etc.), which must also be coordinated with the first group of three. This increased pilot load must be eliminated by a well-adjusted (coupled) flight control system, so that each control organ uncouples one trajectory variable from the others.

4. NECESSARY DISPLAYS AND CONTROLLER AIDS

The situation of the pilot during steep approach conditions can be characterized as follows:

— He must have available a greater amount of information more rapidly than before.

— He must operate more actuators in a more accurate and coordinated way.

Consequently, he requires better displays and control units, as well as an improved flight control system. To a certain extent, the display information can be replaced by control units, and vice versa [16]. Therefore, it is not only necessary to /12
establish the most economical way of providing flight control aids, but it is also necessary to establish the best (cheapest) compromise between the modification of the displays and the modifications of the control system.

State variables	Measurement variables	Replacement variables
Attitude angle	Longitudinal inclination/ transverse inclination/ heading	
Rotational rate components	Pitch, roll, yaw	
Translation velocity in x, y, and z directions	Ground speed / Descent velocity	Heading angle Longitudinal inclination angle
Position coordinate	Oblique distance (DME) y, z guide beam deviation and barometric altitude	Time (markers), radio altitude
Lift	Angle of attack Side slip angle Flap setting, etc.	Ground speed Transverse acceleration
Forward thrust	Thrust (pressure ratio) Defection angle, etc.	x, z acceleration "potential trajectory angle"

Figure 4. Variables for determining the dynamic state of an aircraft during landing approach.

First we will discuss the additional variables which are to be measured for the pilot and the control system. In order to have optimum control of a control loop, it is necessary to continuously know its dynamic state. For an aircraft, this means that the following state variables must be measured:

— the rotation rate around the three axes,

— the three rotation angles,

— the three components of the velocity vector,

— the position of the aircraft, for example, relative to the touchdown point.

In addition, we have the flow state around the wings (representative angles of attack and side slip angles, and flap position as well as flow through the engines), as well as the state of the engines (thrust, deflection angle).

In the case of conventional ILS approach, an aircraft state is stabilized over a long time period, and, therefore, it is sufficient to know the following variables:

— rotation rate and angles around the three axes (pitch angle, roll angle, and heading)

— position coordinates in the y and z directions in the form of deviations from the guiding beam

— replacement for the x coordinate by the time interpolation between approach signals (markers) and altitude information during the last part of the approach (radio altitude as an information consisting of "how far to touchdown")

— the ground speed as a velocity component in the x direction, also a replacement for the information about the flow state over the wings ("how far to flow separation")

— lontigudinal information and headings as replacement variables for the velocity components w and v.

The accuracy requirements on these variables also correspond to the situations that there is sufficient time for stabilizing /13 the approach and for correcting deviations. The accuracy requirements increase as the aircraft approaches the touchdown point.

In the case of a steep and changing approach trajectory, this information must be complemented by the following variables:

— exact velocity measurement in the z direction, i.e., descent velocity or trajectory angle,

— accurate position determination in the x and z directions, i.e., measurement of altitude and distance to touchdown point, position along the nominal trajectory ("how far to the next flight trajectory change")

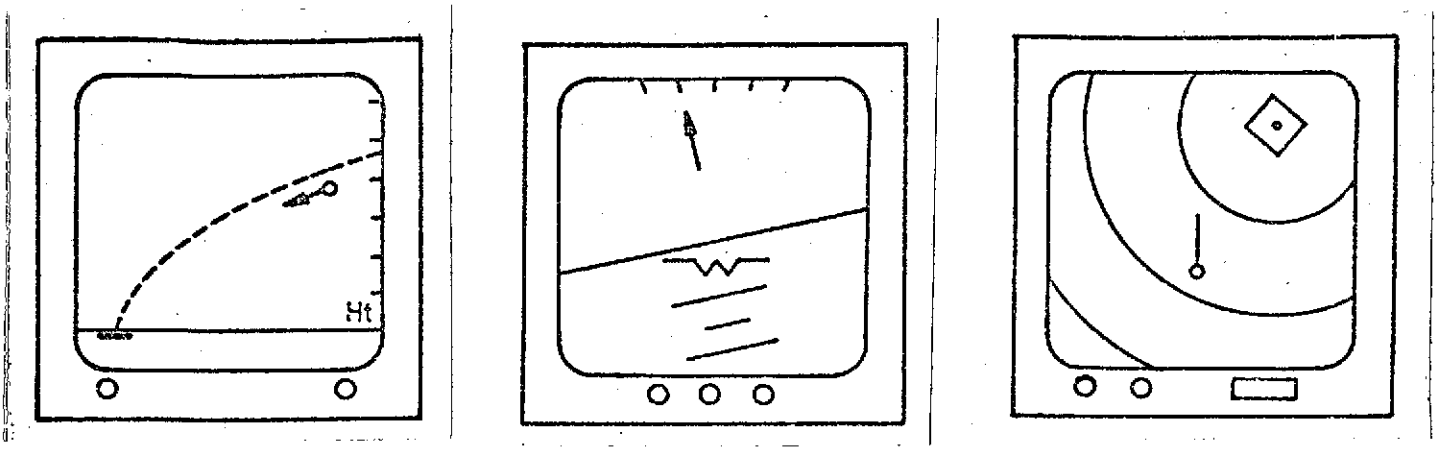
— exact determination of the flow state, i.e., measurement of angle of attack and side slip angle. In particular, the angle of attack gives better information on the state of flow (lift state) than the ground speed [12] at low velocities

— knowledge of the state of the engine, i.e., knowledge of the instantaneous thrust and acceleration capacity (depends on the working point)

— if the trajectory has a sidewise curvature, it is also necessary to know the sidewise deviation and the sidewise velocity.

Since the nominal trajectory varies and control commands can only be given with delays (thrust change, lift change), all of the variables mentioned must be predicted in advance, i.e., the tendency must be known as to how the flight situation will change over the next few seconds. This becomes possible by the additional measurement of the translation acceleration, at least of $\ddot{x}$ and $\ddot{z}$. From this measurement, often a "potential trajectory angle" is derived which, at the same time, constitutes replacement information for the forward thrust and lift information.

All of the information measured must be directed to the flight control system, if the approach is to be controlled automatically. The formulation of predictions represents a conventional measure in control theory for improving the control behavior. If the /14
pilot is to carry out the approach himself, however, or if he is to oversee the flight control system to the extent that he can



Profile display | Vertical situation display | Horizontal situation display

Figure 5. Situation representation in three planes from [16].

take on the control at any time, then it is necessary to also display all of these variables in a suitable way. One example of this is the representation of the flight situation, i.e., the position of the aircraft with respect to the guide beam and with respect to the touchdown point, as well as the display of the velocity vector in the two vertical planes and in the horizontal plane (Figure 5). The representation of the aircraft with respect to the approach profile as seen from the side represents a new method of presentation compared with conventional displays, and was first tested by the U.S. Air Force during the PIFAX program [20]. At the present time, it is also being used in the flight test program of the Bodenseewerks (Figure 6). Here, in addition to the position and velocity vector with respect to the approach trajectory, we also display the angle of attack state variables (lift), as well as the descent velocity and altitude. Displays for the simultaneous representation of the vertical and horizontal situation in one instrument have been suggested by Teldix and by the RAE [16]. In these configurations, the situation representation is combined with control information

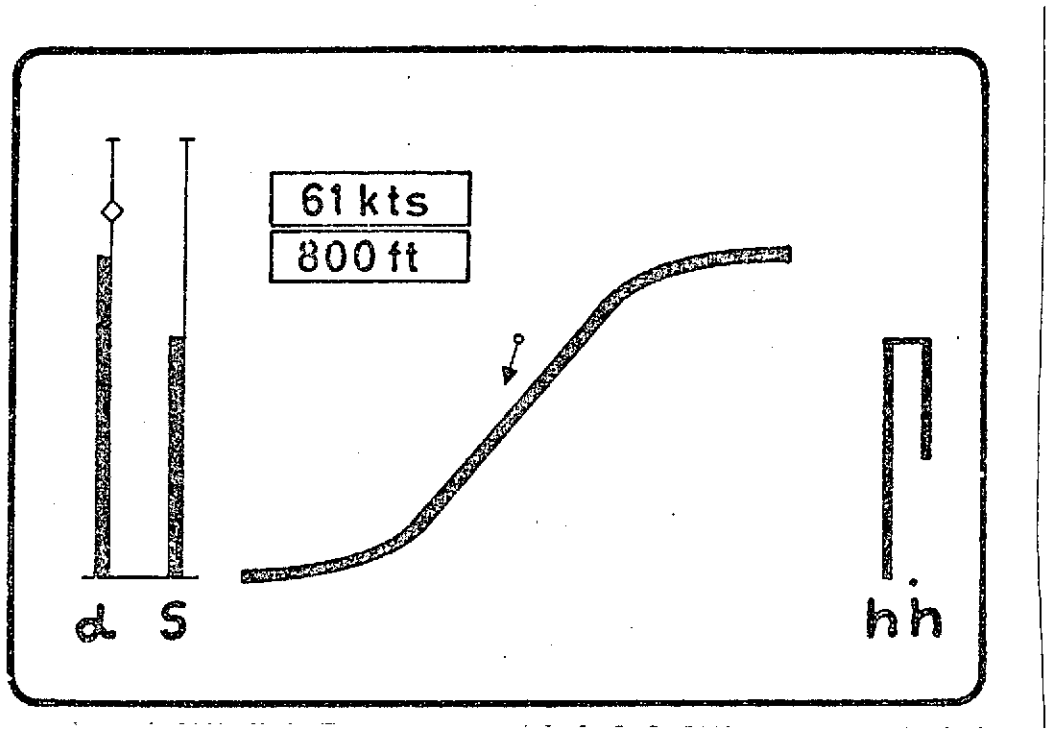


Figure 6. Situation representation as seen from the side for STOL approaches, Bodenseewerk, from [12].

(flight director displays), which gives the pilot the nominal and actual information, as well as the control system deviations produced by generating prediction data. Another example for such an integrated display system was used during the NASA/Boeing program discussed above (Figure 7). This representation is superimposed during the final approach onto a television picture of the landing runway. In all of these displays, the altitude is the most difficult to represent [16], and therefore, it is usually given in digital form.

The previous enumeration of measurement variables and displays represents the maximum requirements for flight control information required during steep approaches, and this can only be brought about by extensive measures and high costs. For example, in order to accurately know the position, velocity /15

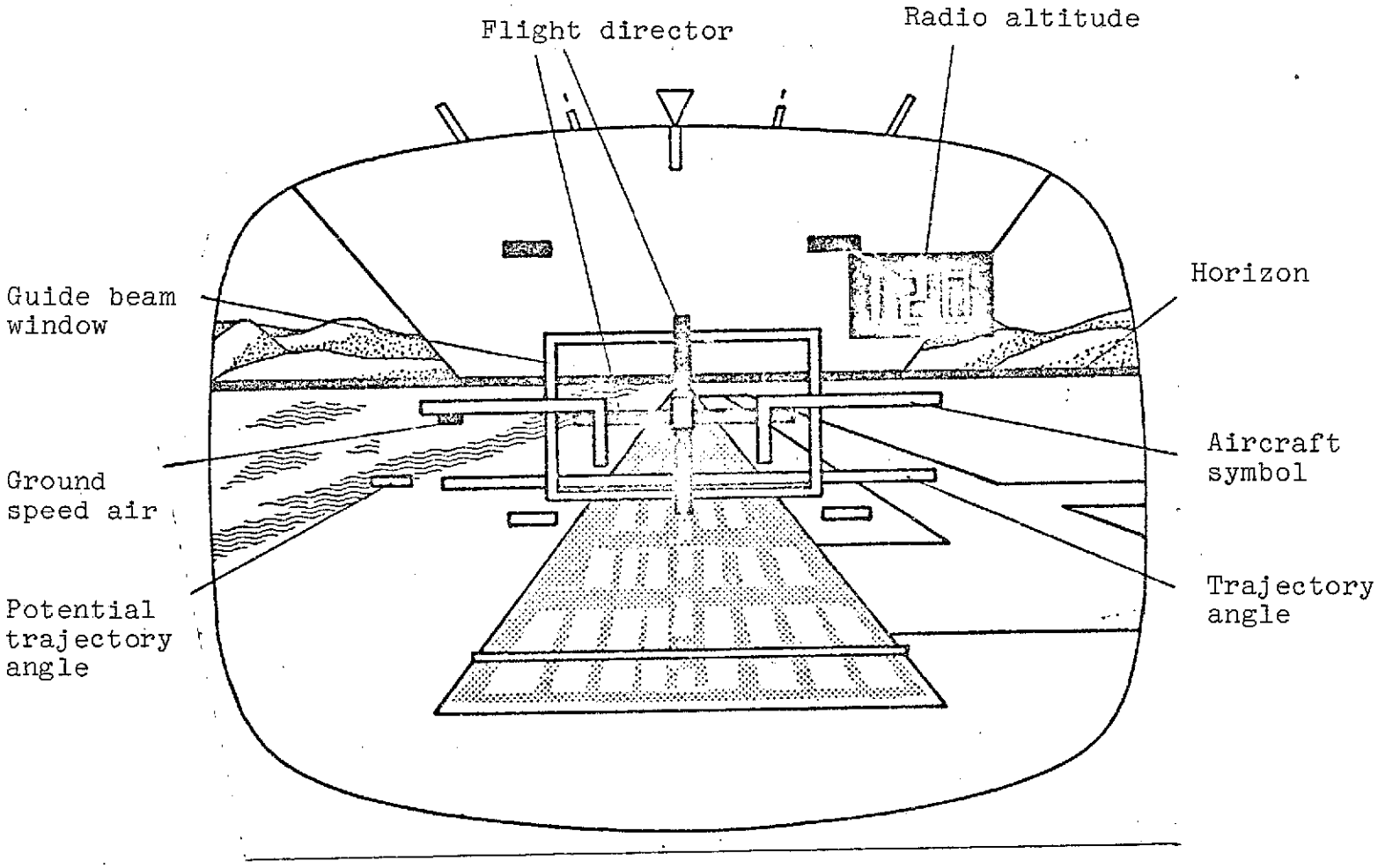


Figure 7. Electronic integrated system from [15].

vector and accelerations, it is necessary to have an inertial platform. This measurement must be supported by a new guide beam system for remote measurements (DME). On the other hand, these more theoretical reflections have been completely supported by experience from test programs made by the airlines.

Economy considerations have led to a reduction in the requirements for steep approaches to approach angles in the range 4 — 6° and to profiles which are (at least piecewise) similar to ILS approaches. During test programs (see above) made with conventional commercial jet aircraft, the following was done:

— the requirement for a guide beam during the upper approach segment was dropped and this trajectory section was calculated using precision navigation methods (area navigation) or even using the measurements of barometric altitude and oblique distance (DME). The upper segment was flown using conventional ILS,

— a conventional flight director was used which was only modified with respect to the broken approach profile, so that shortly before the guide beam break was reached, a discontinuous control signal for trajectory change was produced,

— the requirement for special displays of angle of attack and side slip angle was dropped.

On the other hand, many agencies have stated that it is absolutely necessary to accurately know the descent velocity and that the barometric measurement is insufficient for this.

In the case of steep approach, the effort connected with flight control aids is found to be a true limitation on the achieveable flight performance. Any economical use of this will require a special tradeoff.

5. TASK DIVISION BETWEEN THE PILOT AND THE FLIGHT CONTROL SYSTEM /16

As mentioned above, the effort connected with displays can partially be compensated for by a corresponding effort in the control system. In other words, if savings are to be made in the flight control system (or if it is not reliable enough), then the pilot must be in the position of controlling the aircraft without extensive work using the corresponding complex displays.

Since the pilot should be relieved from subordinate tasks as much as possible, but he should be in the position of being able to correct the trajectory at any time, we have the following maximum requirements for the flight control system: automatic control along the nominal flight trajectory by means of a completely coordinated (coupled) flight control system, for the rotational and translational degrees of freedom, which for example means a complete integration of the "forward thrust controller" within the control system. This concept, for example, has been applied by the Bodenseewerk in a logical fashion. On the other hand, the aircraft flight control system must be controlled by the pilot in such a way that he can influence the individual trajectory parameters such as forward speed and trajectory angle (or descent velocity) independent of each other, i.e., uncoupled from each other, using his primary control organs [19]. The control system must be designed in this way as well as the corresponding displays. The Control-Wheel-Steering (Boeing 737) represents a first attempt at this, which has been built during the NASA/Boeing program. It is possible to control the pitch rate using the control stick. In [6], it was suggested that this principle be developed so that, based on an inertial navigation system, the three components of the velocity vector could be controlled by the pilot through the control system.

Since new developments in the area of control systems are very costly and require much time, attempts were made during the flight programs mentioned above to use available flight control systems. The introduction of direct lift controls was dropped /17 for the most part, however, because their effectiveness is questionable, at least for conventional aircraft. In addition, in some cases, the use of the forward thrust controller was dropped as well [10]. Other agencies absolutely require forward thrust control and automatic trim during steep approach. In order to maintain the work load on the pilot within the limits, and in order to change the approach methods as little as possible, during this year's NASA program, the flight director and flight control system are improved to an extent that the pilot effort during steep approaches is only negligibly different from his work during conventional ILS approach. Here again a compromise must be sought and it is important to carefully trade off how much the flight control system is to be expanded, how the standard operational sequence is to be modified and how much the pilot has to be retrained.

6. NAVIGATION AND TRAFFIC CONTROL PROBLEMS

The NASA test programs and studies and the studies of the American airlines, especially by American Airlines, showed that STOL traffic is only economical if the following conditions can be met [14]:

— the STOL traffic must have advantages for the non-participating public (noise reduction), as well as advantages for the passengers (flight comfort),

— a traffic control system must be developed which provides a safe and accurate control even for increased traffic density, and also relieves the traffic control personnel.

Both points relate directly to flight control. In order /18
for the passenger of jet traffic to change to the STOL traffic, he must be offered a similar degree of comfort as during long range flights. This means that, on the one hand, there can be no extreme flight attitudes during takeoff and landings, which limits the range of possible flight trajectories. Also, the low altitude gusts cannot have a detrimental effect, and the control system must suppress them effectively. In addition, the passenger must be able to recognize clear advantages of STOL traffic in the form of more frequent and on-time connections, as well as reduced flight times. The usually lower travel velocity of STOL aircraft must be compensated by more direct flight trajectories and shorter overall travel times. The STOL routes (Figure 8) flown by Eastern Airlines are an example of a possible shortening of the flight paths. Area navigation must replace the rigid point-to-point navigation on these types of flight paths. This is possible based on present technology using VOR/DME stations and inertial navigation installations, which are at present being installed in mass produced Boeing 747s. Corresponding displays for area navigation using electronic map representations and specifications of the position on the flight path, display of the velocity vector and other numerical data are available and have been tested (Figure 9). Only the high costs prevent the introduction of such navigation aids before the clear economic advantages of STOL traffic can be demonstrated.

Based on the different flight velocities and flight paths, it is difficult to integrate the STOL traffic with conventional traffic. For economic operation, both would have to be separated, in the navigation and approach methods, the traffic control, as well as in the area of landing runways.

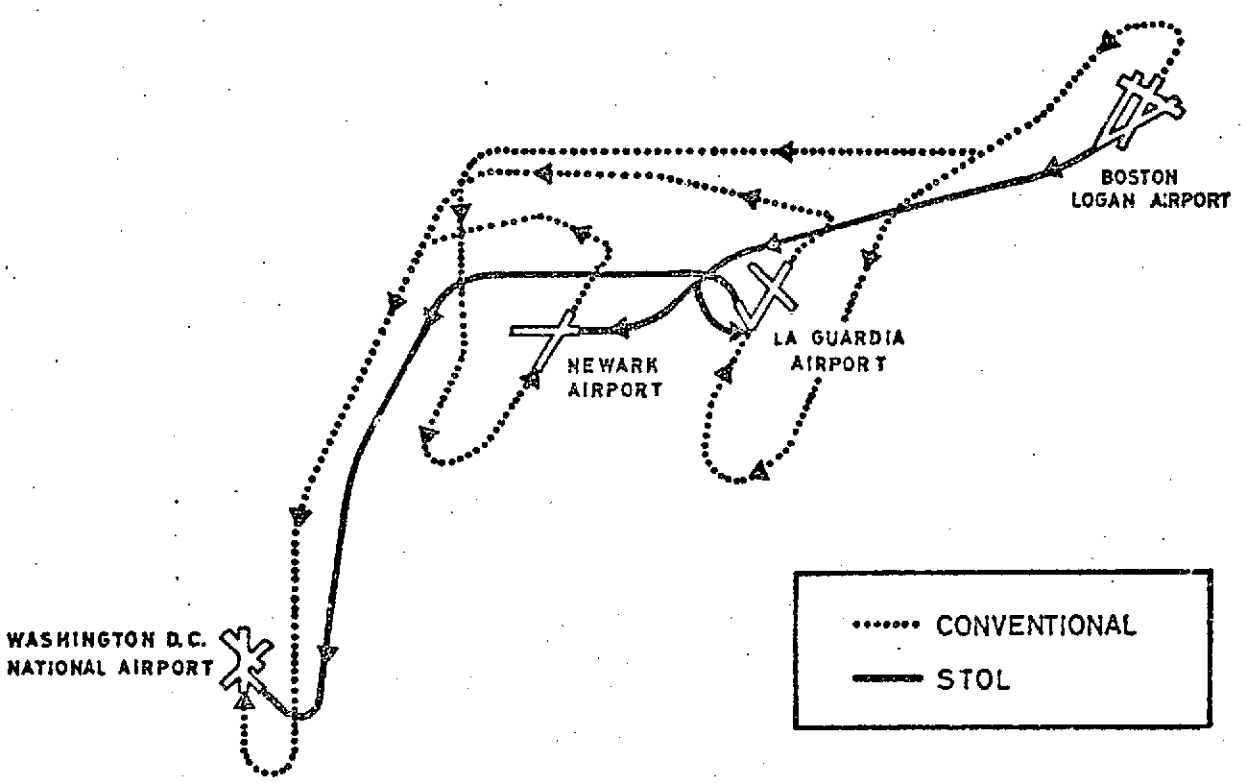


Figure 8. Shortened STOL flight paths. Eastern Airlines test program from [3].

Finally, the traffic control problem still remains to be solved for two reasons. First of all, the advantages of STOL traffic cannot compromise the safety and increase the collision danger. The STOL flights must be on time, or the advantages of STOL flight would be compromised. Also, it would be dangerous to reduce the work of the pilot and at the same time increase the work of the traffic control personnel. This work can only be reduced and the traffic density can only be increased at the same time if the traffic control function is automated considerably. In one project, each individual flight starting at entry into the near field is characterized in time and in space ("four-dimensional navigation") [6], so that if approach takes place

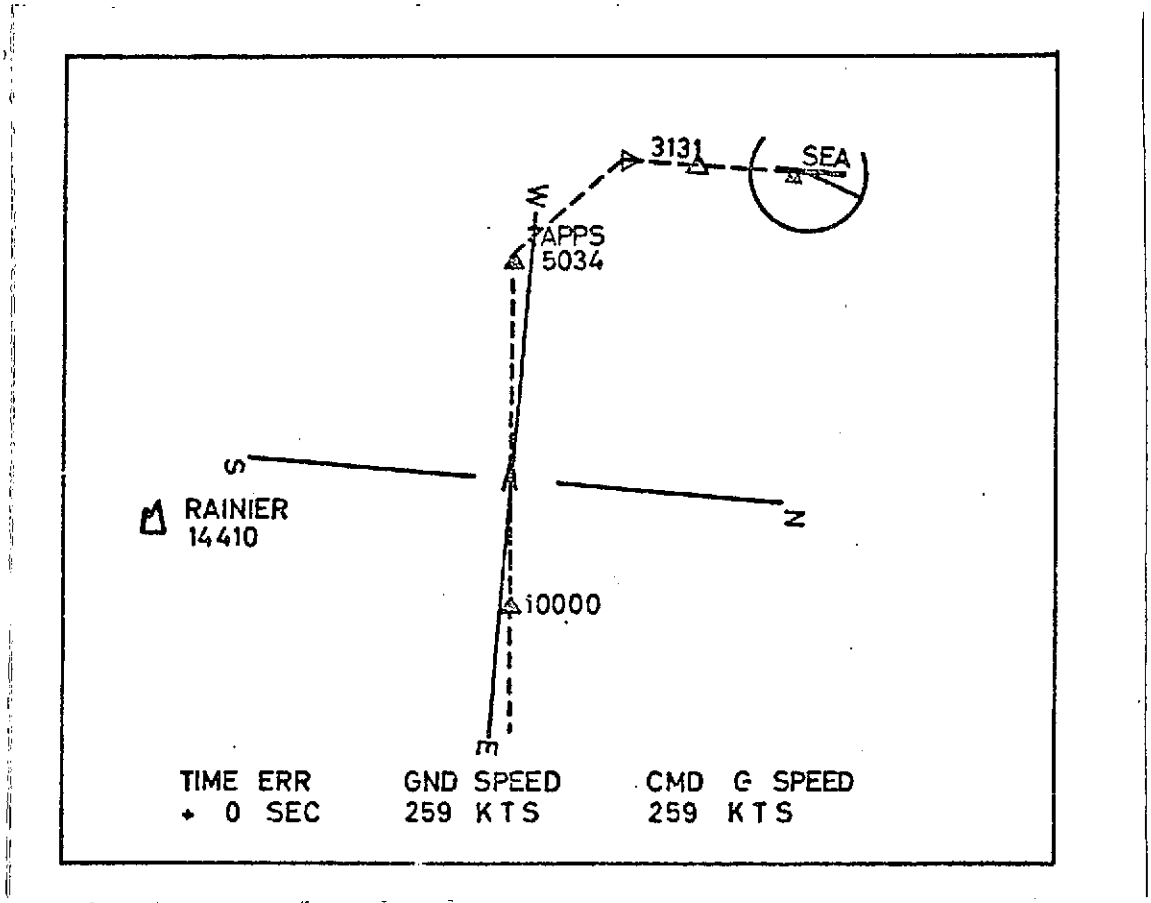


Figure 9. Electronic card representation for area navigation from [6].

along several standardized approach trajectories, it is possible to maintain a fixed sequence (Figure 10). For this, it is necessary to have area navigation and improved navigation aids for the traffic near the airports. In addition, such a "pre-programmed flight traffic operation" increases the reliability requirements for the navigation system, measurement system, the displays, and the flight control system. The increased costs show that these are also a maximum requirement and these cannot be satisfied in the immediate future. Until automatic flight control systems are available, STOL traffic will remain restricted.

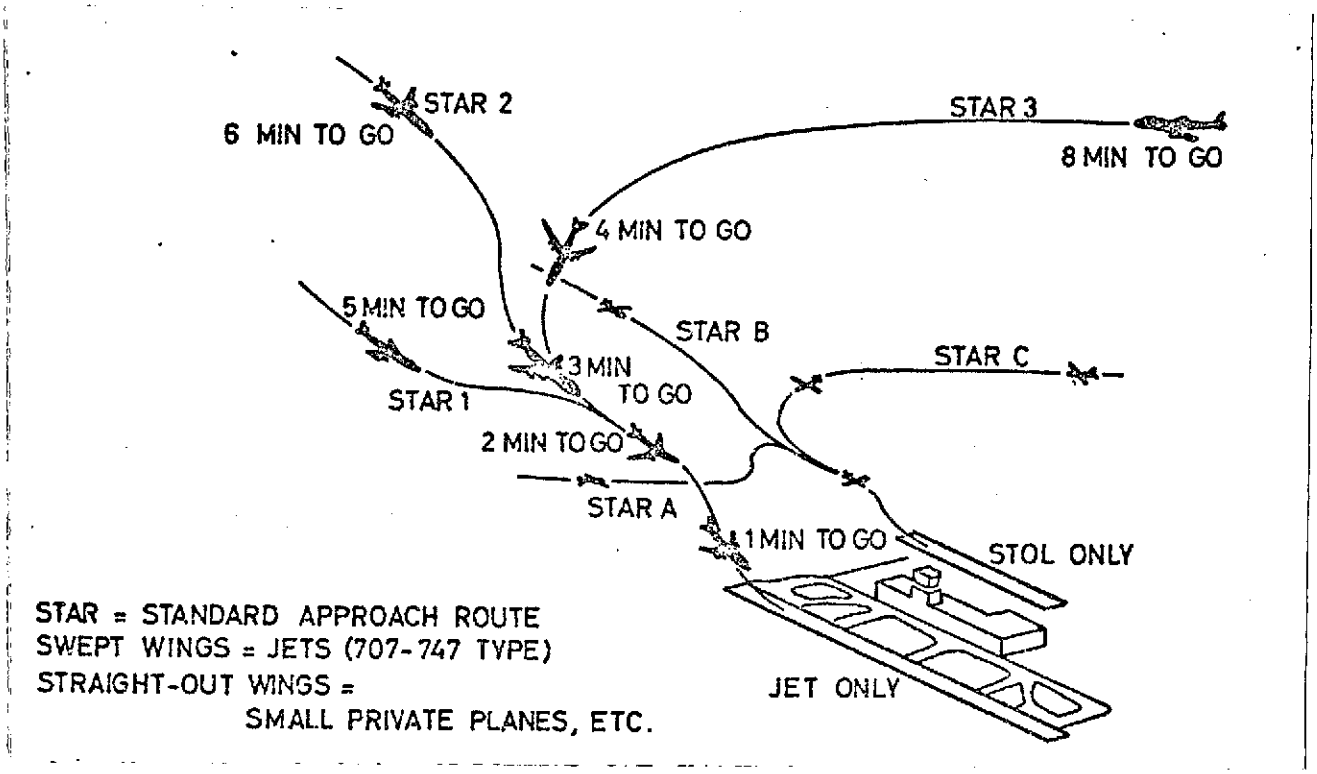


Figure 10. Time-synchronized approach from [6].

7. FUTURE DEVELOPMENT /20

The methods of steep approach discussed before are very close to existing systems and methods, and the development of STOL traffic will not stand still provided an economic advantage exists or if STOL operation is the only way out of the increasing traffic density. The general introduction of area navigation for the regions close to the airport, more precisely the introduction of radio supported inertial navigation systems, will greatly simplify the selection of approach trajectories in the vertical and horizontal plane. At the same time, microwave guide beam systems will make it possible to fly curved approach trajectories [21], which sometimes are optimized for maximum noise reduction and best use of the area around the airport. Using new aircraft especially designed for STOL operation, it will be possible to fly approach angles which are 9° or even 12° along some segments.

Such true steep approaches can no longer be handled using present day aircraft controllers and displays. One must even make a break with the conventional principle of aircraft control, according to which the pilot can dispense at any time with the support of the controller during the approach and can carry out the landing himself. In the case of approach angles above 6°, and especially for curved approach trajectories, the pilot no longer has the capacity of manually flying the aircraft. He requires at least as much controller support in order to directly control the velocity vector of the aircraft. In addition, he must have a detailed and clear display of the instantaneous flight situation, so that he can introduce an emergency maneuver at the right time if there are failures. In other words: the control, display, and navigation systems must operate with high levels of /21 safety. The critical time period during which a failure cannot compromise a function (fail operative) now makes up a major part of the landing time. This time is no longer on the order of 12 seconds, the time between the decision altitude and touchdown for ILS, but now amounts to 120 seconds and more.

Therefore, the problem amounts to specifying a more extensive and better performing flight control system. In addition, the overall system must have a greater degree of reliability.

This problem becomes even more critical if we consider fixed approaches programmed in time, during which the actual time of touchdown is established 10 minutes before and, because of a traffic situation, greater difficulties are produced for traffic control if a deviation maneuver is required during the last part of the approach. The critical time spans for these reliability requirements start at the time where a deviation maneuver from a specified approach trajectory compromises the safety of other approaching aircraft. Therefore, it is also a function of the permissible traffic density in the approach region.

8. FINAL REMARKS

The introduction of steep landings brings about a number of problems which concern the area of aircraft control, which is the support of humans by measurement technology, control technology, and display technology. The possibilities of introducing steep approaches are severely limited by these flight control requirements. These problems are decisive for the economics of STOL traffic.

This is why the first task definitions for steep approaches /22 are relatively modest, so as to be able to use conventional flight control systems as much as possible without substantial modifications. An extension to higher approach angles and higher flight frequencies will only become possible by using new flight control systems. Developments towards true STOL traffic are in process in the areas of aircraft design, control system design, display system design, and navigation system design.

REFERENCES

1. X22 Tri-Service V/STOL Aircraft. Bell Aerospace Report 2127-933073. December, 1969.

2. STOL Demonstration Program. Technical Report, EAL Flight R & D 68-315. March, 1969.

3. The Path to STOL Traffic. Interavia August, 1968 and July 1969.

4. Yaffee, M. L. NASA Building STOL Transports. Aviation Week and Space Technology. September, 1971.

5. Flora, C. C., G. K. L. Kriechbaum, and W. Willich. A Flight Investigation of Systems Developed for Reducing Pilot Workload and Improving Tracking Accuracy during Noise Abatement Landing Approaches. NASA CR 1427, 1969.

6. Clifford, D. R. Approach Path Control for Reduced Noise and Improved Traffic Capacity. AGARD-CP-76-71. 1970.

7. Reduced Noise Approach Profiles Tested. Aviation Week and Space Technology. September, 1971.

8. Brown, D. A. American Advances STOL Studies. Aviation Week and Space Technology. March, 1971.

9. American Study Finds Turboprop STOL Risky for Airline Role. Aviation Week and Space Technology, April, 1972.

10. Elson, B. M. Two-Segment Approach Method Studied. Aviation Week, February, 1973.

11. Schaenzer, G. Integrated STOL Flight Control System. Bodenseewerk TB 000D 704/71. December, 1971.

12. Schaenzer, G. Problems of Integrating Aircraft and Aircraft Control Systems for New Approach Methods. Lecture held at the DGLR Yearly Meeting. October, 1972.

13. Boehret, H. Problems of Producing an Integrated Flight Control System Considering Curved Flight Trajectory Profiles. DGLR/DGON Symposium, New Approach Methods. May, 1973.

14. Brown, D. A. Public Acceptance Key to STOL. Aviation Week and Space Technology. March, 1972.

15. Hamel, P. Noise Abatement Flight Profiles for CTOL and V/STOL Aircraft. DLR FB 71-10.

16. Watters, D. G., and R. Beyer. Displays for Approach and Landing. AGARD-CP-96.

17. Pinsker, W. J. G. Theoretical Assessment of the General Stability and Gust Response Characteristics of STOL Aircraft. RAE-R & M, 3686.

18. Quigley, H. C., et al. Flight and Simulation Investigation of Methods for Implementing Noise Abatement Landing Approaches. NASA TN D-5781. 1970.

19. Schmidt, G., H. Friedel, and G. Schweizer. Control and Flight Control Problems for Future V/STOL Landings Considering Experience with the Do-31. DGLR Yearly Meeting, September, 1969.

20. Knemeyer, S., and G. L. Vingling. Results of the USAF Pilot Factors Program as They Apply to Flight Safety. WPAFB-FDL, 1967.

21. Schaenzer, G. Flight Trajectory Control Device for Producing Curved Flight Path Trajectories with Microwave Landing Systems. DGLR/DGON Symposium on New Approach Methods. May, 1973.

Translated for National Aeronautics and Space Administration under Contract No. NASw-2483 by SCITRAN, P. O. Box 5456, Santa Barbara, California 93108.